Longitudinal shrinkage in fast-grown loblolly pine plantation wood

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Abstract

Genetically improved trees or trees from selected seed stock may grow so fast in intensively managed plantations that they reach sawtimber size in 25 to 30 years or less. Trees harvested at this age contain high proportions of juvenile wood, which when used in solid form, may exhibit excessive longitudinal shrinkage: this adversely affects dimensional stability of wood-based products. This paper provides basic information about loblolly pine longitudinal shrinkage (LS) characteristics, age-LS profiles, and relationships between LS and anatomical properties. Segmented regression equations were developed to describe the relationships between microfibril angle (FA) and age, LS and FA, and LS and age. For this data set, the following were concluded: 1) measured parameters of specific gravity (SG), percentage of earlywood, and FA are sensitive to age: 2) the drier the material, the greater the change in LS for a given change in moisture content, and the younger the material, the greater the variability in LS; 3) LS negatively correlates with SG and positively correlates with percentage of earlywood; 4) stepwise multiple regression indicates that SG and FA would be the best predictors of LS; and 5) a robust regression technique using the relationship between FA and age can predict LS from age.

Wood shrinks differently in all directions (radially, tangentially, and longitudinally). It has been well proven that the juvenile core material in a tree shrinks longitudinally much more than does mature material (4,5,7-9, 11). This can affect the dimensional stability of wood-based products. Pioneering work has been done on theoretically modeling relationships between microfibril angle (FA) and longitudinal shrinkage (LS) (1,2). According to these theories, the prime cause of anisotropy in shrinkage is explained by modeling wood as if it consisted of reinforcing microfibrils in a weak matrix. These studies suggested that observed deviations from the theory could be explained by the effect of the components of the cell wall other than the S2 layer or by changes in the ratio between the elastic moduli of the amorphous matrix of the S2 layer and of the reinforcing microfibrils. Others have built on these earlier works by looking at different species and methods for determining the important factors controlling LS (6, 12, 14, 15).

Based on earlier experimental and theoretical work, abnormal LS is associated with age-related factors, compression wood, FA, and specific gravity (SG). Of these factors, FA appears to be the most significant. Apparently, whatever the species, LS is a highly variable property, and this variability decreases with age. However, few equations defining these relationships have been developed. In this study, we investigated LS and derived equations that will assist in determining the age at which the transition to mature material is completed for loblolly pine (*Pinus taeda* L.). A predictive equation for LS based on age was also determined.

Materials and methods

The specimens were prepared from 21 loblolly pine trees from 21 plantations in the South. The average diameter at breast height (DBH) of the bolts was 0.61

TABLE 1. – *Summary of specific gravity (SG), percentage of earlywood (EW), microfibril angle (FA), and longitudinal shrinkage (LS) tests.*[a]

Age (yr.)	No. of specimens	SG	EW[b] (%)	FA (deg.)	LS — 22.7% EMC[c] (%)	20.3% EMC (%)	15% EMC (%)	11.7% EMC (%)	7.8% EMC (%)	Ovendry state (%)
1	21	0.39 (0.08)	85 (22)	33 (4)	0.092 (0.112)	0.230 (0.125)	0.340 (0.186)	0.451 (0.2.18)	0.595 (0.324)	0.870 (0.467)
2	20	0.39 (0.07)	79 (23)	35 (4.1)	0.054 (0.099)	0.177 (0.142)	0.266 (0.235)	0.388 (0.315)	0.538 (0.407)	0.829 (0.552)
3	21	0.40 (0.08)	74 (23)	35 (3.2)	0.028 (0.1001)	0.138 (0.150)	0.194 (0.233)	0.275 (0.334)	0.400 (0.432)	0.659 (0.590)
4-4.5	21	0.42 (0.09)	67 (29)	36 (3.8)	0.021 (0.099)	0.116 (0.143)	0.150 (0.235)	0.215 (0.310)	0.319 (0.418)	0.566 (0.563)
5-5.5	20	0.45 (0.07)	67 (21)	35 (5.2)	0.008 (0.093)	0.101 (0.132)	0.120 (0.238)	0.170 (0.315)	0.268 (0.424)	0.482 (0.605)
6-6.5	20	0.45 (0.08)	57 (23)	32 (5.1)	-0.003 (0.098)	0.074 (0.154)	0.070 (0.269)	0.117 (0.361)	0.196 (0.502)	0.416 (0.692)
7-7.5	17	0.45 (0.07)	64 (21)	31 (6.2)	-0.002 (0.091)	0.101 (0.175)	0.119 (0.331)	0.171 (0.457)	0.262 (0.636)	0.392 (0.8071)
8-8.5	20	0.48 (0.07)	58 (25)	29 (6.9)	-0.029 (0.096)	0.048 (0.133)	0.045 (0.234)	0.078 (0.302)	0.140 (0.407)	0.328 (0.549)
9-9.5	10	0.48 (0.101)	59 (25)	26 (3.9)	0.017 (0.110)	0.118 (0.155)	0.129 (0.271)	0.180 (0.382)	0.277 (0.543)	0.503 (0.792)
10-11.5	26	0.51 (0.08)	47 (17)	23 (5)	-0.026 (0.091)	0.055 (0.129)	0.059 (0.240)	0.096 (0.346)	0.176 (0.498)	0.369 (0.717)
12-13.5	23	0.53 (0.07)	47 (18)	20 (5.9)	-0.038 (0.064)	0.036 (0.084)	0.026 (0.142)	0.044 (0.188)	0.096 (0.263)	0.260 (0.379)
14-15.5	21	0.53 (0.07)	51 (15)	21 (5.2)	-0.039 (0.049)	0.035 (0.086)	0.028 (0.159)	0.053 (0.201)	0.103 (0.286)	0.265 (0.389)
16-17.5	22	0.54 (0.06)	41 (13)	19 (6.7)	-0.046 (0.037)	0.023 (0.072)	0.021 (0.120)	0.044 (0.151)	0.083 (0.190)	0.229 (0.257)
18-19.5	15	0.52 (0.07)	48 (16)	19 (6.2)	-0.035 (0.044)	0.040 (0.080)	0.046 (0.155)	0.070 (0.194)	0.130 (0.263)	0.295 (0.367)
20-21.5	15	0.50 (0.10)	53 (18)	17 (3.7)	-0.040 (0.033)	0.021 (0.039)	0.021 (0.039)	0.008 (0.078)	0.029 (0.113)	0.059 (0.128)
22+	10	0.47 (0.09)	55 (16)	17 (5)	-0.040 (0.017)	0.013 (0.030)	0.003 (0.047)	0.029 (0.049)	0.057 (0.054)	0.189 (0.072)

[a] Data for SG, EW, FA, and LS are averages: standard deviations are in parentheses.
[b] Percentage of ring that is earlywood.
[c] EMC = equilibriated moisture content.

m (2 ft.). The trees ranged in age from 25 to 28 years. A 5-mm-thick by 280-mm-long (3/16-in-thick by 11-in.-long) slab, centered on a radius and reaching from pith to bark, was cut from each bolt. The radius was selected with preference to wide growth rings, to rings at right angles to the radius, and to freedom from compression wood.

Specimens, which were in most cases one growth ring wide, were serially ripped from the thin slabs with a small hobbyist table saw (kerf 1.5 mm (1 / 16 in.)) to minimize kerf loss. The kerf was centered on the interface of adjacent growth rings with equal material being removed from each ring to the extent possible. Where growth was very slow, specimens contained two or three annual growth increments. For these specimens, the average age of the specimen was used for analysis. The specimens were then trimmed to a 280-mm length. Thus, the final specimen dimensions were 5 mm thick; one, two, or three growth rings wide; and 280 mm long.

The FA for each specimen was measured on the end trim using the techniques described in Senft and Bendtsen (13). This involved light microscopy on thin sections stained with safranin and rapidly ovendried to induce checking in the S2 cell wall layer. Ten measurements were made in each earlywood and latewood band while traversing the growth ring. These measurements were then averaged.

Longitudinal shrinkage, SG, and moisture content (MC) were calculated at various moisture levels. The specimens were exposed sequentially to equilibrated moisture contents (EMC) in environments controlled at 90, 80, 65, 50, and 30 percent relative humidity and 27°C (80°F) and then were ovendried to a constant weight. Weights and longitudinal dimensions were measured at each EMC and when ovendry. Specimens were weighed to the nearest 0.001 g (2.2×10^{-6} lb.), and dimensions were measured on a digital micrometer to an accuracy of 0.025 mm (0.001 in.). Longitudinal shrinkage was based on the percentage of change in dimension from the green condition to each EMC and to the ovendry condition. The SG for each specimen was calculated based upon ovendry weight and dimensions when green. Finally, MC was calculated at each EMC from weight at time of test and ovendry weight.

Results and discussion

The average test results for SG, percentage of earlywood, FA, and LS for each EMC level and the ovendry state are summarized by age in Table 1. The LS values had the typically large variation observed by other researchers. The data collected were analyzed for patterns and trends. Various regression techniques were applied to the data to determine the relationship between FA and age and the influence of SG, FA, age, percentage of earlywood, and MC on LS. The results of the statistical analysis are summarized in Table 2.

Parameter relationships

Table 1 shows decreasing average percentage of earlywood and increasing average SG as age increased until age 18. Specific gravity ranged from 0.39 to 0.54. Percentage of earlywood ranged from 85 to 41 percent. Figure 1 shows the relationship between FA and age for the test specimens. Microfibril angle is reasonably constant for a time during the juvenile and mature material growth periods, but the angle is at different microfibril levels for each growth period. Between the juvenile growth and the mature growth, a gradual transition of decreasing FA with increasing age occurs.

Earlier work by Bendtsen and Senft (3) suggested that a segmented least-squares regression can be used to establish a curve fit to FA-age relationships. Using the data and earlier work as a guide, a segmented least-squares regression was fit to the data as shown in Figure 1. It was assumed that for a period of time for both the juvenile and mature material, the relationship between FA and age was constant. The segmented regression indicates that from age 1 to 5, the average

FA for these data is about 35°; from age 5 to 13, the average FA follows a decreasing trend that can be described as: FA = 44.25 - 1.921 × age: after age 13, the average FA is about 19°. The regression therefore suggests that for these data, after age 13, the transition from juvenile to mature wood is complete.

For these data, 25° provides a reasonable separation between material assumed to be juvenile and mature wood. Except for a transition zone, most juvenile wood specimens had an FA greater than 25° and most mature wood specimens had an FA less than 25°. Substituting 25° into the segmented regression corresponded to an age of 10 years. This division of 25° and 10 years was used for all further modeling.

At the initial drying level, some specimens elongate rather than shrink, as has been explained by Barber and Meylan (1). These authors suggest that when wood is wet, the amorphous matrix has a relatively low modulus of elasticity. Changes in the MC of wood near the fiber saturation point can result in either elongation or shrinkage. However, as the material dries further, the amorphous matrix stiffens and the material consistently decreases in length. Most large LS values per change in percentage MC occurred after wood was dried past the 11.7 percent EMC level (Table 1).

Through dependent variable analysis, it was found that variation in LS between trees is much larger than that within a tree at a highly significant level (Table 2,

TABLE 2. – *Summary of statistical analysis of variability and regression equations*[a]

| Analysis | Name of value | Ovendry state | EMC level (%) | | | | |
			7.8	11.7	15	20.3	22.7
1. Within- and between-tree variability	F-value	70.48	55.37	46.22	40.5	31.41	32.44
	F-level	$p<0.0001$	$p<0.0001$	$p<0.0001$	$p<0.0001$	$p<0.0001$	$p<0.0001$
2. Regression of LS on FA	Intercept (A)[b]	0.02686	-0.03882	-6.04473	-0.04548	-6.03181	-0.05198
	FA (B)	0.00863	0.004756	0.003322	0.002538	0.00276	0.000374
	FA2 (C) (FA>25)	0.03573	0.02988	0.02222	0.01653	0.008424	0.007636
	r^2	0.2132	0.2283	0.2255	0.2284	0.2546	0.2358
	F-level	$p<0.0001$	$p<0.0001$	$p<0.0001$	$p<0.0001$	$p<0.0001$	$p<0.0001$
3. Regression of LS on SG	Intercept (A)	1.2406	0.9043	0.6732	0.5176	0.3494	0.1464
	SG (B)	-1.7105	-1.4201	-1.1037	-0.8791	-6.5638	-0.3209
	r^2	0.07667	0.09811	0.1083	0.1246	0.1488	0.1053
	F-level	$p<0.0001$	$p<0.0001$	$p<0.0001$	$p<0.0001$	$p<0.0001$	$p<0.0001$
4. Regression of LS on EW	Intercept (A)	0.197	0.01176	-0.02986	-0.05235	-0.02037	-0.06473
	EW (B)	0.004055	0.003805	0.003115	0.002649	0.00177	0.001019
	r^2	0.0292	0.04773	0.05845	0.07666	0.09942	0.07202
	F-level	$p<0.0029$	$p<0.0001$	$p<0.0001$	$p<0.0001$	$p<0.0001$	$p<0.0001$
5. Stepwise regression of LS on FA and SG	Intercept (A)	-0.3623	-0.06979	-0.01855	0.02113	0.03973	-0.06097
	FA (B)	0.0294	-0.4736	-0.4315	-0.3968	-0.2627	-0.1193
	SG (C)		0.01947	0.01382	0.009921	0.006185	0.004144
	F-level	$p<0.0001$	$p<0.0001$	$p<0.0001$	$p<0.0001$	$p<0.0001$	$p<0.0001$
6. Asymptotic regression of LS on age	Intercept (A)	0.8702	0.5834	0.4358	0.3228	0.2235	0.0957
	Age (B)	-0.06286	-0.05088	-0.04252	-0.03377	-0.02171	-0.01671
	Age 2 (C) (Age > 10)	0.00111	0.004145	0.007315	0.007995	0.005733	0.0072

[a] EMC = equilibrated moisture content: LS = longitudinal shrinkage: FA = microilbril angle; SG = specific gravity: EW = percentage of ring that is earlywood.
[b] The constants A, B, and C are the coefficients for analysis equations 1 through 6.
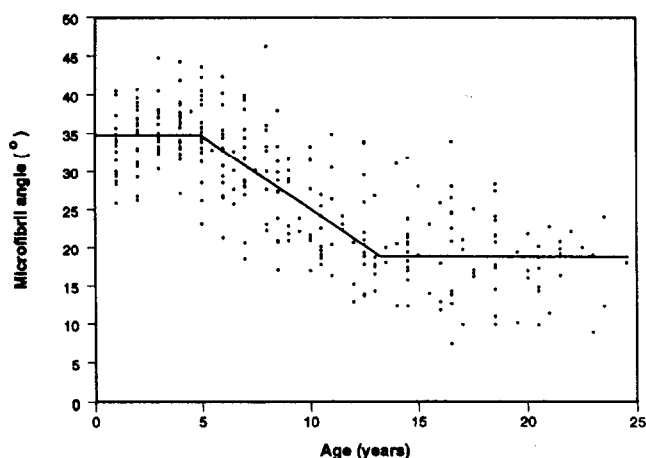

Figure 1. – Relationship of microfibril angle to age.
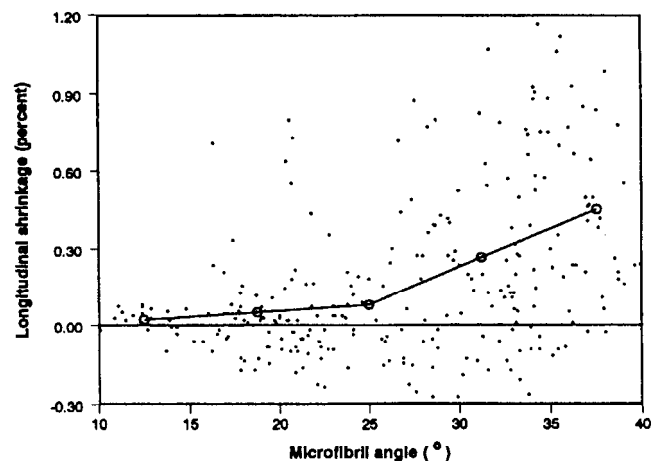

Figure 2. – Relationship of longitudinal shrinkage to microfibril angle at 8 percent equilibrated moisture content.

analysis 1). Because of this large variability between trees, the regression curves are only indicative of trends in this data set and are not strong predictors of species properties.

An example of the LS-FA relationship for the 8 percent EMC level is shown in Figure 2. For all EMC levels, the average LS increased very slowly with an increase in FA for small FAs, then increased at a steeper slope with larger FAs. A segmented least-squares regression was applied to determine the most favorable combination of parameters to predict LS based on the transitional FA previously determined of $25°$ and age 10 years. When FA $\leq 25°$, LS = A + B × FA; when FA $>25°$, LS = A + 25B + C(FA -25). A, B, and C are constant coefficients *determined* from the data. The actual values are listed in Table 2. For all EMC levels, the amount of variability in the data increased as the FA increased. Despite the considerable variability in the data, the curve fits the overall trend in the data quite well (Fig. 2). The result of the regression analysis of LS and FA for the various EMC levels is tabulated in Table 2, analysis 2, and shown in Figure 3. These results show that shrinkage increased with increasing FA.

A simple linear regression adequately describes the behavior of SG and LS. The fit of the regression relationships to LS and SG at the different EMC levels is shown in Table 2, analysis 3, and Figure 4, where LS = A + B × SG. The regression results show that LS had a highly significant negative correlation to SG. However, the r^2 value indicates that only a small percentage of the overall variability in the data has been explained. The specimens with the lowest SG tended to have the highest LS, whereas specimens with the highest SG had the lowest LS. This is the reverse of what is expected with transverse shrinkage. This can be explained by the tendency of specimens with low SG to have larger FAs. The LS-SG relationship also showed steeper slopes at the low EMC levels. The

specimens with high SG were less sensitive to moisture changes than were the specimens with low SG.

As with SG data, a simple linear regression adequately describes the relationship of percentage of earlywood to LS (Table 2, analysis 4). The LS data have a highly significant positive correlation to the percentage of earlywood. However, again the r^2-value indicates that little of the overall variability in the data is explained. The relationship between LS and percentage of earlywood is also sensitive to EMC level. The lower the percentage of earlywood, the less sensitive the relationship is to moisture changes. Also, the closer the EMC level comes to ovendry, the more sensitive the relationship is to moisture changes.

Prediction of LS

A predictive relationship that would allow the estimation of LS from the measured parameters (SG, FA, percentage of earlywood, and age) was investigated.
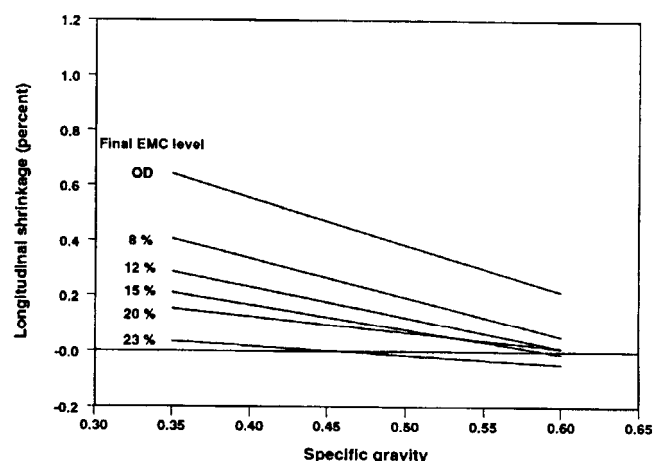

Figure 4. – Relationship of longitudinal shrinkage to specific gravity at ovendry (OD) state and various equilibrated moisture content (EMC) levels.
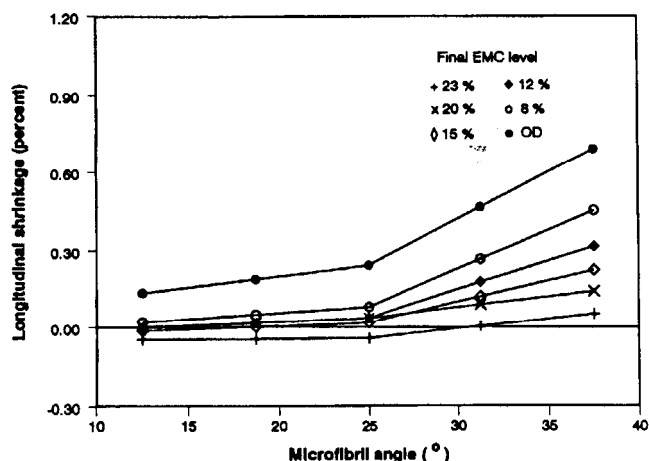

Figure 3. – Fitted curves for relationship of longitudinal shrinkage to microfibril angle at ovendry (OD) state and various equilibrated moisture content (EMC) levels.
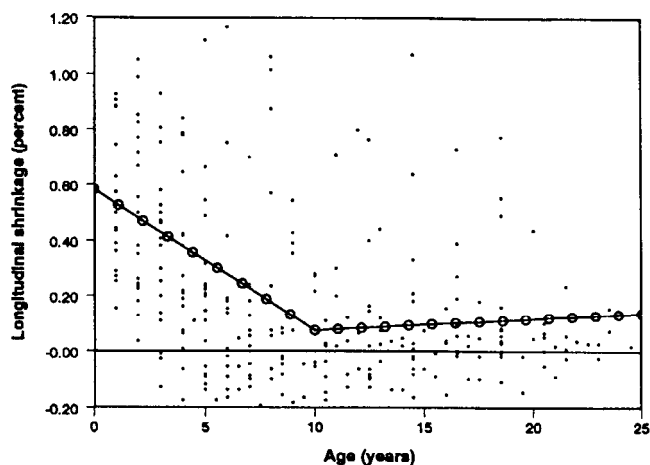

Figure 5. – Relationship of longitudinal shrinkage to age at 8 percent equilibrated moisture content.
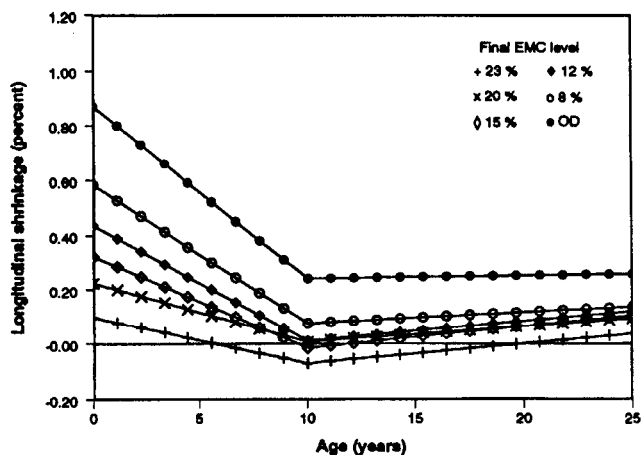
Figure 6. – Fitted curves for relationship of longitudinal shrinkage to age at ovendry (OD) state and various equilibrated moisture content (EMC) levels.

Every parameter does not, however, have the same effect on IS. To determine the relative importance of these parameters, a stepwise multiple regression technique was employed. It was found that for the ovendry state, only FA was significant at the 0.15 significance level, whereas at other EMC levels, FA and SG were statistically significant (Table 2, analysis 5). Judging from this analysis, apparently FA and SG are the best predictors of LS, but this form of predictive equation is not convenient to implement because the FA is harder to measure than any other factor. Therefore, another method of prediction was investigated.

Figure 1 shows that FA and age appear to have a strong relationship. Therefore, we chose to use age to replace FA as a variable to predict IS. To do this, we used a robust iterative reweighted least-squares regression analysis (10), in which the inverse of the distance of the residual from the fitted line is used as a weighting factor and iterated. In other words, a weighting technique is applied to test data that minimizes the effect of outliers while determining an estimate of an average predictive relationship.

The example of the curve fit to the data for the 8 percent EMC level is shown in Figure 5. Figure 5 shows that this technique fits the data adequately for predictive purposes. The results of the robust regression analysis for all EMC levels are given in Table 2, analysis 6, and shown in Figure 6. The common point used (as determined in Fig. 1) was 10 years. When age was ≤10 years, LS = A + B × age was used; when age was >10 years, LS = A + 10B + C(AGE - 10). Longitudinal shrinkage declined quickly with increase in age until 10 years, then almost no change or a slight trend toward an increase in LS occurred. The shape of the age-LS relationship was sensitive to changes in MC

(Fig. 6). The most sensitivity to changes in LS for a given change in age occurred at the lowest EMC levels.

Conclusions

For this particular data set, the following conclusions were drawn:

1. Measured parameters of SG, percentage of earlywood, and FA are sensitive to age.

2. The drier the material, the greater the change in LS for a given change in MC.

3. The younger the material, the greater the variability in IS.

4. LS is negatively correlated to SG and positively correlated to percentage of earlywood, but this explains only a small portion of the total variability in LS results.

5. Stepwise multiple regression indicates that SG and FA would be the best predictors of IS.

6. A robust regression technique using the relationship between FA and age can be used as a method for predicting LS from age.

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